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An X-Ray Source for Lithography Based on a Quasi-Optical Maser Undulator

P. SPRANGLE, B. HAFIZI* AND F. MAKO**

Plasma Theory Branch
Plasma Physics Division

**Science Applications International Corp., McLean, VA*

***FM Technologies, Inc., Alexandria, VA*

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We propose the use of electromagnetic waves as an undulator in order to generate x-rays in the wavelength range required for fabrication of integrated circuits. The configuration consists of a quasi-optical maser cavity through which a beam of relativistic electrons is made to propagate, spontaneously emitting x-rays of the desired energy. For 5'' silicon wafers covered with a sensitive resist such as PBS, this translates into a throughtput of 26 wafers/hr using an aggressive stepper. The scaling of x-ray power with wavelength indicates that the throughput can be increased substantially using resists which are sensitive to shorter wavelength x-rays.

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AN X-RAY SOURCE FOR LITHOGRAPHY BASED ON A QUASI-OPTICAL MASER UNDULATOR

I. Introduction

A major contributor to the tremendous developments taking place in our ability to process information is the miniaturization of semiconductor devices marketed by the electronics industry. It is now recognized that over the next few decades the economic well-being of the United States is dependent on its ability to maintain a leadership position in the fast-developing technology for fabricating smaller and cheaper integrated circuits (IC) (see Ref. 1).

A process by which IC's are mass produced is lithography. Using this technique, a predetermined pattern can be rapidly replicated on the surface of a semiconductor chip using a beam of radiation or particles. A reliable, efficient and compact source of radiation or particles is critical to the economic viability of lithography. This is especially so because of the high capital expenditure required for the sources necessitated by further miniaturization.

In this report we propose a novel design concept for a source of x-ray radiation for the purposes of lithography. In order to motivate the design concept and to provide a comparison with other sources presently being considered, the following section is devoted to a brief description of the salient aspects of the lithographic technique. Section III describes the x-ray sources currently under study and/or development. Our proposed scheme is detailed in Sec. IV, followed by a derivation of the x-ray power formula in Sec. V. In Sec. VI we consider the availability of the two major components (electron beam and electromagnetic undulator) required by the proposed scheme, and we present parameters for an actual device based on a preliminary analysis of the power-formula scaling. In Sec. VII we compare our design-parameters with an x-ray source based on a conventional bending-magnet storage ring. Our conclusions are contained in Sec. VIII.

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II. Lithography[2]

The crystal-growing industry routinely provides silicon crystals about 5" or more in diameter. Once a single-crystal ingot is grown, it is sliced into thin wafers, which are then used for device fabrication. Planar technology consists, for example, in selective introduction of dopant atoms into small precisely predetermined areas of the silicon surface to form regions of p- and n-type material. Dopant atoms can be introduced simultaneously into many separate, small regions of a wafer. Therefore, the use of larger diameter wafers and smaller device dimensions minimizes processing cost per device.

The technique for replication of a predetermined pattern on a silicon wafer is referred to as lithography. The pattern may correspond, for example, to an opening for introduction of dopant atoms by diffusion or implantation. Lithography consists in the application of a thin film of a radiation-sensitive plastic -- called a photoresist -- onto the surface of the wafer. The photoresist is then exposed to radiation through a mask, bearing the desired feature, to create a shadow image on the resist.

A. Resolution

Current state-of-the-art miniaturization requirements by the IC industry call for the ability to resolve submicron minimum features of patterns to be replicated. However, for mass-production of critical, leading-edge circuits for computers, memories, signal processors and other devices, resolutions approaching ≤ 0.1 μm will be required. Resolution, therefore, is a determining factor in the quest for greater device density. However, as is well-known, diffraction provides a fundamental barrier for resolution. If d is the line width of the feature on the mask to be replicated and λ is the wavelength of the radiation, the diffraction angle is λ/d, so that if s is the mask-to-resist separation, the blur on the

resist is $(\lambda/d)s$. Thus, to reduce blur, it is necessary to use short wavelength radiation (x-rays) or energetic particle beams.

B. Sources

As far as resolution is concerned, x-ray radiation or particle beams are satisfactory sources. It is, however, necessary to consider other factors such as throughput and yield in order to be able to select the most appropriate source for lithographic purposes. Direct-write with tightly focussed electron or ion beams is frequently used for extremely high-resolution processes. The wavelength λ of an electron of momentum p is $\lambda = h/p$ where h is Planck's constant. Thus, for a 20 keV electron beam $\lambda \approx 2.5 \times 10^{-2}$ Å. With such short wavelengths, computer-controlled particle beams are ideal for making high-quality patterns on masks which are then used for resist exposure in quantity. However, the main problem with the electron-beam direct-write process for mass production is that it is slow compared to parallel exposure through a mask. In addition, particle beams spread out upon impinging on a resist, and there is also some backscattering and thus possible damage to the mask.

III. X-Ray Lithography

Since x-ray sources have high throughput compared to direct-write techniques, we now concentrate on three sources of x-ray radiation that are envisioned for lithography. These are: a) electron-impact (x-ray tube), b) high-temperature plasma, and c) synchrotron radiation. To compare these, we list the important characteristics that must be considered in making a choice between different sources.

i) Emission intensity

ii) Efficiency of x-ray generation and usage

iii) Spectral character of radiation (lines, continuum, etc.)

iv) Energy range of emitted photons

v) Source size (important for resolution)

vi) Emission solid angle (determines collimation and exposure area)

vii) Pulsed or cw

In comparing the different x-ray sources, we shall consider the material polymethyl methacrylate (PMMA) which is a popular, high-resolution resist suitable for submicron work. To fully expose PMMA one requires 1 J/cm^2 of 12 Å radiation. More generally, the range of useful photon energies is 0.5 - 1.5 keV (20-8 Å). Photon energy influences resist absorption which, along with the intensity, determines the exposure time. In common with ordinary photography, faster resists than PMMA are found to exhibit poorer resolution. We now enumerate the properties of the three common sources of x-ray radiation.

A. Electron-Impact

X-ray tubes were the first to be used for x-ray lithography. The radiation is uncollimated and is in the form of lines (bound-to-bound transitions) and a continuum (free-to-free transitions in the nuclear Coulombic field). X-ray tubes are inefficient, with typically less than 1% of the electron beam energy being converted into (total) x-ray radiation.

B. High-Temperature Plasmas

X-ray radiation from plasmas at 10^6-10^7 °K is in the form of a line spectrum (bound-to-bound transitions), continua with a high-energy cut-off (free-to-bound transitions), and a continuum (free-to-free, bremsstrahlung). Heating of the plasma is via a discharge (as in a z-pinch) or a high-power laser,[3] and the radiation is spread over a large solid angle (2π to 4π). The process is necessarily pulsed with a lifetime of 10-100 ns for discharge heating and 1-10 ns for laser heating. Efficiencies are in the range of 1-10%.

Some of the problems associated with high-temperature plasma lithography are the following:

i) Contamination of mask and/or resist by debris from the plasma

ii) Low repetition rate

iii) Thermal response of mask and/or resist to very intense, pulsed heating

iv) Significant shot-to-shot variability of plasma sources.

C. Synchrotron Radiation

Synchrotron radiation is generated by electrons in synchrotron accelerators and storage rings. It is basically magnetic bremsstrahlung due to the curved motions of the particles in the bending (dipole) magnets. Although the radiation process is efficient, usage of the emitted radiation is quite inefficient due to the large fraction that is lost onto the vacuum chamber walls. Since the radiation is highly collimated ($\lesssim$ 1 mrad for a 1 GeV electron beam), the mask-wafer separation and wafer flatness are less critical than with x-rays from a point-source with highly-diverging rays. The spectrum is continuous so that filters and/or mirrors must be used to select the desired wavelength band for lithography work.

In existing and proposed storage rings electrons are typically injected at low energy (~ 150 MeV) and then accelerated to about 1 GeV while the bending magnets are ramped up to about 4-5 T. These are designed for compactness, with linear dimensions on the order of several meters. Superconducting magnet designs are also available and somewhat more compact, although there is the added cost and extra space for the cryogenic system. Thus far, the most important source of x-ray synchrotron radiation is that provided by dedicated storage rings to be found in many national laboratories throughout the world. However, these machines are extremely expensive and occupy a great deal of space. On the other hand, the commercial storage rings for x-ray lithography are only now becoming available.

Since there are inherent difficulties associated with each of the three x-ray sources we have mentioned, in what follows we propose the use of an electromagnetic undulator as another means of generating x-rays which may prove to be suitable for lithographic applications.

IV. X-Ray Radiation in an Electromagnetic Undulator

The use of periodic undulators and of wigglers to achieve higher brightness (energy radiated per unit bandwidth per unit solid angle) and to modify the spectral character of the radiation by storage rings is by now well-established.[4] Due to complexity and construction costs of electromagnets (conventional or superconducting) recent developments in the fabrication of high-field, rare-earth cobalt permanent magnets[5,6] have led to their almost-universal use as insertion devices in storage rings.

Defining the dimensionless magnetic field parameter

$$K = \frac{|e|B_o\lambda_o}{2\pi mc^2}, \tag{1}$$

where e is the charge and m is the rest-mass of an electron, c is the speed of light in vacuo, B_o is the peak magnetic induction and λ_o is the period of the planar undulator or wiggler, the wavelength λ of the radiation emitted along the beam direction is given by

$$\lambda = \frac{\lambda_o(1+K^2/2)}{2\gamma^2}, \tag{2}$$

where γ is the relativistic mass factor. Typically, λ_o ranges over 1-10 cm so that for x-ray radiation in the required range (8-20 Å) electron energies upwards of several GeV are required. On the other hand, one might use lower energy electrons, say 150 MeV, and use extremely short-period insertion devices. However, to maintain the same magnetic field strength there has to be a corresponding decrease in the gap spacing between opposite poles of the magnet.[6] This implies very thin filamentary electron beams and correspondingly high electron-beam brightness.

As an alternative to the permanent magnet designs mentioned in the preceding, we propose herein to employ a high-power electromagnetic wave of moderate wavelength ($\lesssim$ 1 mm) to generate x-ray radiation in the required wavelength range using moderate energy electrons ($\lesssim$ 1/4 GeV). It is expected that with use of moderate energy electrons and one of a variety of recently-developed, efficient, high-power sources of coherent radiation, a compact source of x-ray radiation may be designed for commercial use without an excessive capital outlay.

V. Technical Discussion

As is well-known, the radiation emitted by a charged particle in instantaneous circular motion is confined to cone of half-angle $1/\gamma$ about the direction of dominant motion.[7] It is also well-known that for motion in a periodic magnetic or electromagnetic field the transverse particle orbit is periodically deflected through an angle

$$\theta_d = K/\gamma. \tag{3}$$

We can now distinguish two limiting cases. For $K \lesssim 1$ we see that the transverse angular deflection of the particle lies within the natural opening angle of the emitted radiation. In this case, the insertion device is referred to as an undulator and the emitted radiation is confined to a very narrow angle about the direction of propagation and is thus of high brightness. For an insertion device for which $K > 1$ (referred to as a wiggler) we see from Eq. (3) that the emitted radiation is spread over an angle K/γ, which may be considerably larger than the natural opening angle $1/\gamma$, depending on the magnitude of K. In the limit $K \gg 1$, the wiggler radiation is similar to that from a bending magnet where particles undergo substantial deflection on traversing the bending field.

For the electromagnetic pump wave to be considered herein, one can define an equivalent parameter K as in Eq. (1). It turns out that for our configuration $K \ll 1$, so that the electromagnetic pump behaves like an undulator. Therefore, unlike wiggler fields and the commercially available bending-magnet designs, the radiation from the electromagnetic undulator would be highly collimated and entirely available for resist exposure. Additionally, for $K \ll 1$ the higher harmonics are negligible compared to the fundamental.

To evaluate the radiated power for the case of the electromagnetic undulator, we refer to Fig. 1. This is a schematic (not to scale) of a configuration wherein the electron beam propagates along the z-axis and interacts with the electromagnetic pump field stored in the cavity. If L is the interaction length, the cavity mirror on the right-hand side includes an orifice of diameter $2L/\gamma$ to permit extraction of the x-ray radiation. The opening in the mirror is connected to a Bragg reflector,[8] which is simply a long, corrugated metallic tube, to effectively plug the resonant cavity against microwave power loss. Alternatively, the orifice may be connected to a tube across which a jet of neutral gas is pumped. If the gas density is sufficiently high, the microwaves will be reflected due to cutoff if the microwave electric field exceeds the breakdown field for ionization of the neutral gas.[9,10]

From a well-known formula of electrodynamics the instantaneous power radiated by a single electron in arbitrary, relativistic motion is given by[11]

$$P = \frac{2e^2}{3c} \gamma^6 \left[\dot{\underline{\beta}}^2 - (\underline{\beta} \times \dot{\underline{\beta}})^2\right], \tag{4}$$

where $\underline{\beta} = \underline{v}/c$ is the particle velocity normalized to the speed of light, and $\dot{\underline{\beta}} = \dot{\underline{v}}/c$, where $\dot{\underline{v}} = \frac{d}{dt}\underline{v}$ is the acceleration. Making use of the Lorentz force formula, Eq. (4) may be rewritten as

$$P = \frac{2e^4}{3m^2c^3} \gamma^2 \left[(\underline{E} + \underline{\beta} \times \underline{B})^2 - (\underline{E}\cdot\underline{\beta})^2\right], \tag{5}$$

where $\underline{E}$ and $\underline{B}$ are the electric and the magnetic fields. Since the x-ray radiation field is small compared to the electromagnetic undulator field, we may neglect the excited radiation fields in Eq. (5). For the undulator field we take plane waves of the form

$$\underline{E} = E_o \sin(k_o z + \omega_o t)\hat{e}_x, \tag{6}$$

$$\underline{B} = -\frac{cE_o k_o}{\omega_o} \sin\left(k_o z + \omega_o t\right)\hat{e}_y, \tag{7}$$

where E_o is the amplitude of the electric field, ω_o is the radian frequency and $\underline{k}_o \equiv (0,0,k_o)$ is the wave-vector. $\hat{e}_z$ is a unit vector along the direction of propagation of the electron beam, with $\hat{e}_x$ out of the plane of the paper and $\hat{e}_y$ in the plane of the paper. We note that the electric and the magnetic field may be obtained from the following vector potential

$$\underline{A} = \frac{c}{\omega_o} E_o \cos\left(\underline{k}_o \cdot \underline{r} + \omega_o t\right)\hat{e}_x, \tag{8}$$

where $\underline{r}$ is the radius vector. Since the vector potential is not an explicit function of the x coordinate, the canonical momentum along the x-axis is conserved, whence

$$\beta_x \equiv v_x/c = (K/\gamma)\cos\left(\underline{k}_o \cdot \underline{r} + \omega_o t\right), \tag{9}$$

where

$$K = \frac{|e|(cE_o/\omega_o)}{mc^2}, \tag{10}$$

is the undulator parameter [cf. Eq. (1)]. To evaluate the power according to the formula in Eq. (5) we make use of the Lorentz equation and after a simple analysis we obtain, for a single electron,

$$P \approx \frac{e^2 \gamma^2 \omega_o^2 K^2}{3c} (1 + \beta_z)^2. \tag{11}$$

The distribution in frequency and angle of energy radiated by the particle is obtained from[12]

$$\frac{d^2\varepsilon_s}{d\Omega_s d\omega_s} = \frac{e^2\omega_s^2}{4\pi^2 c}\left|\int_{-L/2c}^{L/2c} dt\ \hat{n} \times (\hat{n} \times \underline{\beta}) e^{i\omega_s\left[t - \frac{\hat{n}\cdot\underline{r}(t)}{c}\right]}\right|^2, \quad (12)$$

where $\hat{n}$ is the unit vector in the direction of observation, and L is the length over which the electron interacts with the undulator. It is important to note that ω_s in Eq. (12) refers to the radian frequency of the scattered radiation (in the x-ray region), which is to be distinguished from the frequency of the electromagnetic undulator, denoted by ω_o in Eqs. (6)-(8). Expressing the unit vector $\hat{n}$ in terms of the polar (θ) and azimuthal (ϕ) angles,

$$\hat{n} = \hat{e}_z\cos\theta + (\hat{e}_y\sin\phi + \hat{e}_x\cos\phi)\sin\theta,$$

the distribution of the scattered radiation for $\theta \lesssim \frac{1}{\gamma}$ is given by

$$\frac{d^2\varepsilon_s}{d\Omega_s d\omega_s} \simeq \frac{1}{c}\left[\frac{e\omega_o LK\ \gamma}{\pi c(1+\gamma^2\theta^2)}\right]^2\left[1 - \frac{4\gamma^2\theta^2\cos^2\phi}{(1+\gamma^2\theta^2)^2}\right]\left(\frac{\sin x}{x}\right)^2, \quad (13a)$$

where

$$x \equiv \frac{\omega_o L}{c}(1 + \beta_z)\left[\frac{\omega_s(1 - \beta_z\cos\theta)}{\omega_o(1 + \beta_z)} - 1\right]. \quad (13b)$$

From Eqs. (13) we find that for long interaction lengths ($L\omega_o/c \gg 1$) the scattered radiation has a peak centered at

$$\omega_s = \frac{\omega_o(1 + \beta_z)}{(1 - \beta_z\cos\theta)},$$

$$\simeq \frac{4\gamma^2\omega_o}{1+\gamma^2\theta^2}. \quad (13c)$$

It must be noted that the forward scattered wavelength predicted by Eq. (13c) is half of that given by Eq. (2). This is well-known and is due to the traveling-wave nature of the electromagnetic undulator considered in this Section.

It is important to note that the frequency distribution given by Eq. (13) pertains to a single electron. The determination of the actual frequency distribution, in general, presents a complex problem. The factor $(\sin x/x)^2$ in Eq. (13a) indicates a line width on the order of $\lambda_o/2L$ about the central frequency (13c). For long interaction lengths, however, a number of other mechanisms limit the line width. Besides the damping due to the emission of radiation itself, there are several other causes which broaden a line. These include Doppler broadening, collisional broadening, and radiative widths induced by the high power microwaves inside the resonator cavity.

It is useful to express the power emitted as x-ray radiation, Eq. (11), in terms of the power in the electromagnetic pump rather than the undulator parameter K. To do so, we assume the fundamental Gaussian (resonator) mode is proportional to $\exp(-\, r^2/\sigma^2)$ where σ is the spot-size. It is simple to show that the undulator power and the undulator parameter K are related via

$$P_u = \left(\frac{m\omega_o K}{4e}\right)^2 c^3 \sigma^2, \tag{14}$$

whence the total power (in x-rays) of an electron beam of current I_b emitted over a length L of interaction is expressible as

$$P_{x\text{-ray}} = \frac{64|e|^3 \gamma^2 I_b L}{3\sigma^2 \beta_z m^2 c^5} P_u, \tag{15}$$

where use has been made of Eqs. (11) and (14). For applications it is necessary to refine this formula in two respects. First, in order to take into account the variation of the spot-size of the undulator field inside the resonator, we assume the waist to be at the center of cavity, z=0. From elementary diffraction theory, we have

$$\sigma(z) = \sigma_o(1+z^2/z_R^2)^{1/2}, \tag{16}$$

where σ_o is the waist and $z_R = \pi\sigma_o^2/\lambda_o$ is the Rayleigh range corresponding to microwaves of wavelength λ_o. Substituting Eq. (16) into Eq. (15) and averaging over the interaction length L, one obtains

$$\langle P_{x\text{-ray}}\rangle = \frac{32\pi|e|^3 I_b P_u}{3\beta_z m^2 c^5 \lambda_s} \tan^{-1}(L/2z_R), \tag{17}$$

where λ_s *is wavelength of the x-rays.*

A further refinement pertains to the angular distribution of the x-rays. From Eq. (13a) the power radiated per unit solid angle (in terms of the electrons' time) is given by

$$\frac{dP_{x\text{-ray}}}{d\Omega_s} \simeq \frac{2}{\pi}\frac{e^2}{c}\,|\dot{\beta}|^2\,\frac{1}{(1+\gamma^2\theta^2)^3}\left[1-\frac{4\gamma^2\theta^2\cos^2\phi}{(1+\gamma^2\theta^2)^2}\right].$$

Integrating over the cone of semi-angle $1/\gamma$ around the forward direction, Eq. (17) is modified to

$$\langle P_{x\text{-ray}}\rangle = \frac{25\pi|e|^3 I_b P_u}{3\beta_z m^2 c^5 \lambda_s} \tan^{-1}(L/2z_R),$$

or, in practical units.

$$\langle P_{x\text{-}ray}\rangle[W] = 0.045\,\frac{I_b[A]P_u[MW]}{\lambda_s[\text{Å}]}\,\tan^{-1}(L/2z_R), \tag{18}$$

where the x-ray radiation power is in watts, the electron beam current is in Amperes, the undulator stored power is in megawatts, and the x-ray wavelength is in Ångstroms.

VI. Design Parameters for Electromagnetic Undulator

As a concrete example of a synchrotron radiation source based on the electromagnetic undulator we present a set of design parameters which would be useful for x-ray lithography. There are basically two main components in our proposed device, the electromagnetic pump wave (undulator) and the electron beam. The goal is to have a powerful source of x-rays to be able to expose a commercially interesting number of wafers. Bearing this in mind and noting the scaling of the x-ray-power formula in Eq. (18) we consider each of these components separately.

For the undulator we have examined several sources of radiation. A good candidate is a pulsed CO_2 laser since gigawatt power levels are readily available from such a source. One of the problems, though, with using such high power levels is the difficulty in designing beam-line optical elements that can operate at high powers.

Our present choice for the undulator is the quasi-optical gyrotron.[13] Quasi-optical gyrotrons employ an open resonator cavity containing a gyrating electron beam which propagates perpendicular to the resonator axis. Among the attractive features of this source are high cw operating powers and high efficiency. Quasi-optical gyrotrons are routinely and reliably operated at the Naval Research Laboratory.[14] A schematic of the NRL quasi-optical gyrotron is shown in Fig. 2.

The other major component of the x-ray source is the electron beam. With the use of a short-wavelength electromagnetic undulator, we require moderately energetic electron beams at high average current levels. For electron beam energies of interest ($\lesssim$ 1/2 GeV) race-track microtrons may be appropriate. Typically, microtrons are limited to very low currents ($\lesssim$ 1 mA), and the linacs that are suitable are fairly expensive. Storage rings appear to be most suitable for our purposes.[15] A closed vacuum

chamber threads through the components of the storage ring which include the bending magnets and the rf cavity. Electron injection can be below the energy of operation in which case the ring is used to accelerate the particles to their final energy within several minutes. The lifetime of the beam may be several hours depending on the average pressure in the ring.

If we assume the stored (circulating) power in the quasi-optical cavity is 1/4 GW, using a 1/4 GeV, 1/2 A (average current) storage ring, from Eq. (18) we find that the power emitted as x-ray radiation is about 3/4 W. From Eq. (13c) we find that if the x-rays are centered at about 12 Å then the undulator (that is, the microwave radiation in the quasi-optical resonator) has a wavelength λ_0 of about 1.2 mm, which should be readily available with current quasi-optical technology. In making use of Eq. (18) we have assumed that the intramirror separation L in the quasi-optical cavity is much larger than the Rayleigh range z_R of the microwaves. This is true provided the waist of the microwaves is on the order of or less than several centimeters and L is on the order of 1 meter or longer. It is important to note that for $L/z_R \gg 1$, $\tan^{-1}(L/2z_R) \to \pi/2$ and the power formula in Eq. (18) is then independent of the cavity dimensions, the microwave spot-size and wavelength, and the electron beam energy. However, the latter two parameters determine the required x-ray wavelength, which is constrained by the composition of the resist material.

If we consider using gas breakdown instead of the Bragg reflector to stop microwave leakage through the mirror orifice, then for this configuration the electric field of the microwaves passing through the orifice in the right-hand cavity mirror exceeds the breakdown field of a typical gas at 20 torr. At this pressure, x-ray absorption is negligible, but the plasma density exceeds the microwave frequency and may therefore completely eliminate the loss of microwaves from the cavity.

VII. Comparison of X-Ray Sources for Lithography

In order to put the expected performance of the electromagnetic undulator x-ray source in perspective, we now briefly compare such a device with a conventional, bending-magnet source, such as a storage ring.

We assume the silicon wafer diameter is 5" and divided into chips of area A_C = 3X3 cm^2. When such a wafer is covered with a high-quality resist such as PMMA (resist sensitivity ≈ 1 J/cm^2) and placed at about 8.5 m from the source, we find that with the design parameters of Sec. VI the chip exposure time T_E is 12.3 sec. The throughput T of the lithography process, in terms of wafers/hr, can then be estimated from[16]

$$T = \frac{3600}{T_{L/U} + T_G + \frac{A_W}{A_C}\left(T_S + T_A + \frac{\sqrt{A_C}}{V} + T_E\right)},$$

where

	Aggressive	Very Aggressive
$T_{L/U}$ = wafer load/unload time, (sec),	20	12
T_G = global alignment time, (sec),	6	3
T_S = stage acceleration and settle time, (sec),	1/5	1/10
T_A = chip alignment time, (sec),	1/2	1/5
V = stage velocity, (cm/sec),	1/2	10

and A_W is the area of the wafer.

The columns on the right of the table indicate typical values for an aggressive and for a very aggressive stepper used in exposing the chips on a wafer.

Using an aggressive stepper, the wafer throughput is found to be 12 wafers/hr. With a more sensitive resist such as PBS (polybutene-ℓ-sulfone; resist sensitivity $\leq$ 100 mJ/cm^2) the throughput rises to 26 wafers/hr, which compares favorably with plasma and with storage ring throughputs. It is of interest to note that the demands on the quasi-optical gyrotron and the electron beam can be significantly reduced by using a very aggressive stepper. For example, a very modest gyrotron (50 MW) and electron beam (100 mA, 1/4 GeV), used in conjunction with PBS and a very aggressive stepper, have a throughput of 8 wafers/hr.

VIII. Conclusion

In this report we propose a novel application of an electromagnetic undulator; namely, as an x-ray source for lithography in the fabrication of high-density integrated circuits. The preliminary conclusion of this work is that it may very well be possible to design such a compact source of x-rays with a commercially-attractive throughput. A significant attribute of this system is that its throughput can be substantially enhanced should resists sensitive to shorter wavelength x-rays be available. In such a case it is necessary to adjust appropriately either the microwave wavelength in the quasi-optical maser or the electron beam energy.

In closing, we mention several problem areas requiring further investigation:

(i) Heat loading of the resonator mirrors in the quasi-optical cavity.

ii) Effect of the transverse distribution of the undulator field on electron motion and the generated x-rays.

iii) Effect of finite electron-beam emittance on x-ray emission.

iv) System design and cost for commercial applications.

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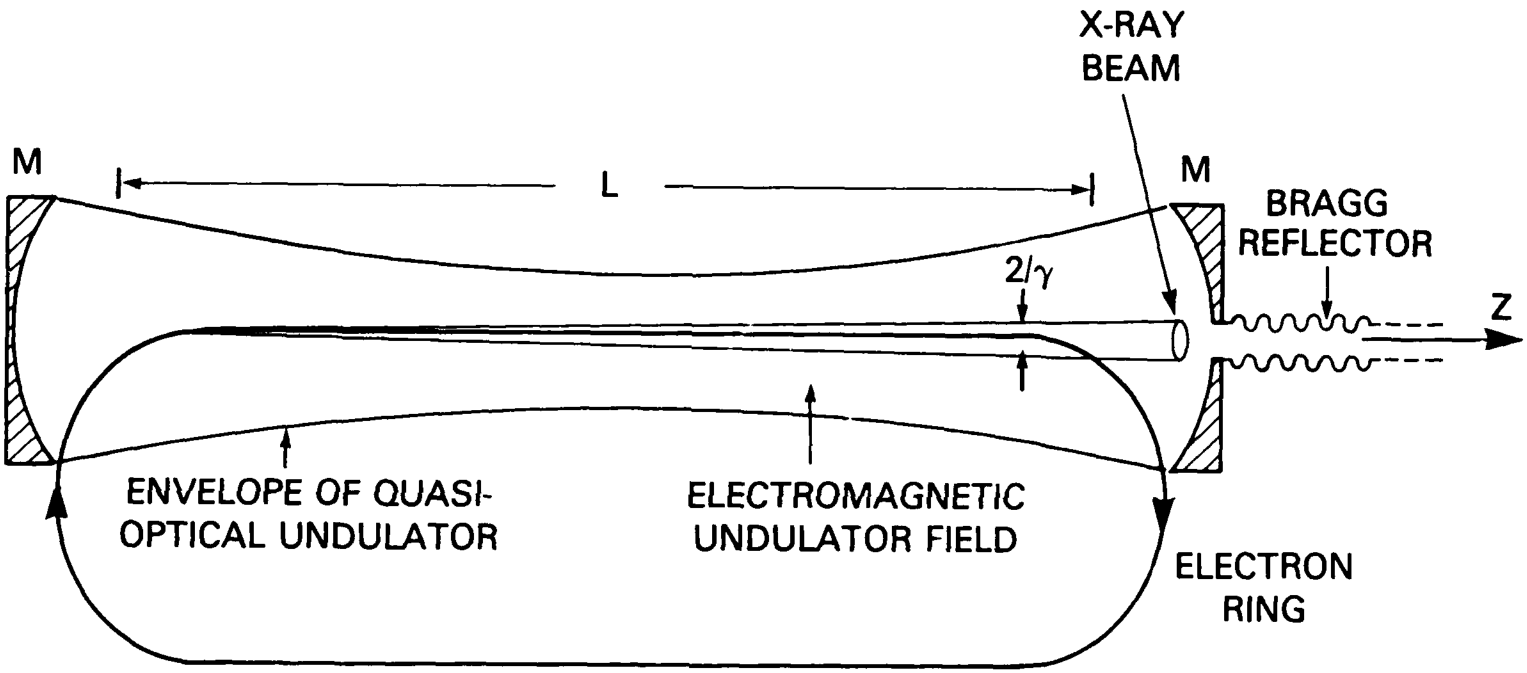

Fig. 1 Schematic top-view of an electron ring (thick line) interacting with the electromagnetic-undulator field inside a quasi-optical resonator cavity bounded by mirrors M. The x-ray radiation is confined to a cone of half-angle $1/\gamma$, γ being the electron beam relativistic factor. L is the interaction length. The function of the Bragg reflector is to reduce the loss of microwave power through the orifice in the right-hand mirror. It may be possible to replace the quasi-optical gyrotron with a CO_2 laser.

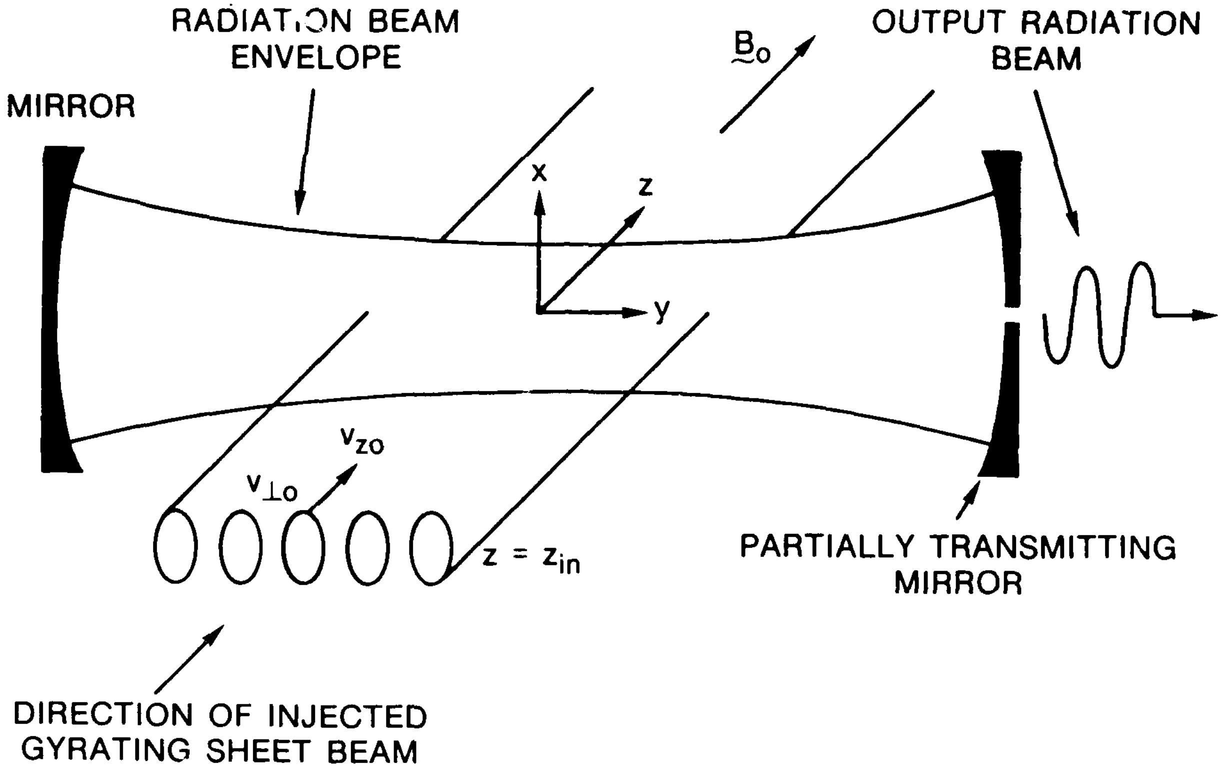

Fig. 2 Schematic of the quasi-optical gyrotron. The electron beam propagates along the magnetic field (~ 5 T) which is directed transverse to the axis of the resonator. Extremely high circulating power levels (~ 100 MWs) can be achieved at short wavelengths (~ 1 mm) with this configuration. The opening in the mirror allows for out-coupled radiation.

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Stanford, CA 94305

Dr. Ross H. Labbe
Rockwell International/Rocketdyne Div.
6633 Canoga Avenue, FA-40
Canoga Park, CA 91304

Dr. Willis Lamb
Optical Sciences Center
University of Arizona
Tucson, AZ 87521

Dr. H. Lancaster
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Dr. D. J. Larson
Deptartment of Physics
University of Virginia
Charlottesville, VA 22901

Dr. J. LaSala
Physics Dept.
U. S. M. A.
West Point, NY 10996

Dr. Bernard Laskowski
M.S. 230-3
NASA-Ames
Moffett Field, CA 94305

r. Michael Lavan
U.S. Army Strategic Def. Command
ATTN: Code CSSD-H-D
P. O. Box 1500
Huntsville, AL 35807-3801

Dr. Ray Leadabrand
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

Dr. Kotik K. Lee
Perkin-Elmer
Optical Group
100 Wooster Heights Road
Danbury, CT 06810

Dr. K. Lee
Los Alamos Nat. Scientific Lab.
Attn: X-1 MS-E531
P. O. Box 1663
Los Alamos, NM 87545

Dr. Barry Leven
NISC/Code 20
4301 Suitland Road
Washington, D.C. 20390

Dr. B. Levush
Dept. of Physics & Astronomy
University of Maryland
College Park, MD 20742

Dr. Lewis Licht
Department of Physics
Box 4348
U. of Illinois at Chicago Cir.
Chicago, IL 60680

Dr. M. A. Lieberman
Dept. EECS
Univ. of Cal. at Berkeley
Berkeley, CA 94720

Dr. Anthony T. Lin
Dept. of Physics
University of California
Los Angeles, CA 90024

r. Chuan S. Liu
Dept. of Physics & Astronomy
University of Maryland
College Park, MD 20742

r. D. D. Lowenthal
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. A. Luccio
Brookhaven National Laboratory
Accelerator Dept.
Upton, NY 11973

Dr. A. Lumpkin
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Phil Mace
W. J. Shafer Assoc., Inc.
1901 N. Fort Myer Drive
Arlington, VA 22209

Prof. J.M.J. Madey
117 Physics Bldg.
Duke University
Durham, NC 27706

Dr. R. Mako
205 South Whiting Street
Alexandria, VA 22304

Dr. Joseph Mangano
Science Research Laboratory
1600 Wilson Blvd.
Suite 1200
Arlington, VA 22209

Dr. Siva A. Mani
Science Applications Intl. Corp.
1040 Waltham Street
Lexington, MA 02173-8027

Dr. J. Mark
Lawrence Livermore National Lab.
Attn: L-477
P. O. Box 808
Livermore, CA 94550

Dr. T. C. Marshall
Applied Physics Department
Columbia University
New York, NY 10027

Dr. Xavier K. Maruyama
Dept. of Physics
Naval Postgraduate School
Monterey, CA 93943

Dr. Neville Marzwell
Jet Propulsion Lab.
MS 198-330
4800 Oak Grove Drive
Pasadena, CA 91109

Dr. A. Maschke
TRW
Mail Stop 01-1010
1 Space Park
Redondo Beach CA 90278

r. K. Matsuda
GA Technologies Inc.
P.O. Box 85608
San Diego, CA 92138

Dr. John McAdoo
8560 Cinderbed Road, Suite 700
Newington, VA 22122

Dr. D. B. McDermott
Electrical Engineering Dept.
University of California
Los Angeles, CA 90024

Dr. J. K. McIver
Dept. of Physics & Astronomy
Univ. of New Mexico
800 Yale Blvd. NE
Albuquerque, NM 87131

Dr. C. McKinstrie
Department of Mechanical Engineering
University of Rochester
Rochester, NY 14627

Dr. B. McVey
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. David Merritt
Space & Naval Warfare Command
Attn: PMW 145A
Washington, DC 20363-5100

Dr. John Meson
DARPA
1400 Wilson Boulevard
Arlington, VA 22209

Col Thomas Meyer
SDIO/DEO
The Pentagon, Rm. 1E180
Washington, DC 20301-7100

Dr. F. E. Mills
Fermilab
P.O., Box 500
Batavia, IL 60510

Dr. D. R. Mize
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, CA 90265

Dr. Mel Month
Brookhaven National Laboratories
Associated Universities, Inc.
Upton, L.I., NY 11973

Dr. B. N. Moore
Austin Research Assoc.
1901 Rutland Dr.
Austin, TX 78758

Dr. Gerald T. Moore
University of New Mexico
Albuquerque, NM 87131

Dr. Warren Mori
1-130 Knudsen Hall
U.C.L.A.
Los Angeles, CA 90024

Dr. Philip Morton
Stanford Linear Accelerator Center
P.O. Box 4349
Stanford, CA 94305

Dr. Jesper Munch
TRW
One Space Park
Redondo Beach, CA 90278

Dr. James S. Murphy
National Synchrotron Light Source
Brookhaven National Laboratory
Upton, NY 11975

Prof. J. Nation
224 Phillips Hall
School of Elec. Eng.
Cornell University
Ithaca, NY 14850

Dr. R. Neighbours
Physics Department
Naval Postgraduate School
Monterey, CA 93943

Dr. George Neil
TRW
One Space Park
Redondo Beach, CA 90278

Dr. Kelvin Neil
Lawrence Livermore National Lab.
Code L-321, P.O. Box 808
Livermore, CA 94550

Dr. W. M. Nevins
L-639
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. Brian Newnam
MSJ 564
Los Alamos National Scientific Lab.
P.O. Box 1663
Los Alamos, NM 87545

Dr. W. Nexsen
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. Milton L. Noble (2 copies)
General Electric Company
G. E. Electric Park
Syracuse, NY 13201

Dr. K. O'Brien
Div. 1241 SNLA
Albuquerque, NM 87185

Dr. John D. O'Keefe
TRW
One Space Park
Redondo Beach, CA 90278

Dr. T. Orzechowski
L-436
Lawrence Livermore National Lab.
P. O. Box 808
Livermore, CA 94550

Prof. E. Ott (2 copies)
Department of Physics
University of Maryland
College Park, MD 20742

OUSDRE (R&AT)
Room 3D1067, The Pentagon
Washington, D.C. 20301

Dr. A. J. Palmer
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, CA 90265

Dr. Robert B. Palmer
Brookhaven National Laboratories
Associated Universities, Inc.
Upton, L.I., NY 11973

Dr. J. Palmer
Hughes Research Laboratory
Malibu, CA 90265

Dr. Richard H. Pantell
Stanford University
Stanford, CA 94305

Dr. Dennis Papadopoulos
Astronomy Department
University of Maryland
College Park, Md. 20742

Dr. P. Parks
GA Technologies
P.O. Box 85608
San Diego, Ca 92138

Dr. John A. Pasour
Mission Research Laboratory
8560 Cinderbed Road
Suite 700
Newington, VA 22122

Dr. C. K. N. Patel
Bell Laboratories
Murray Hill, NJ 07974

Dr. Richard M. Patrick
AVCO Everett Research Lab., Inc.
2385 Revere Beach Parkway
Everett, MA 02149

Dr. Claudio Pellegrini
Brookhaven National Laboratory
Associated Universities, Inc.
Upton, L.I., NY 11973

Dr. S. Penner
Center for Radiation Research
National Bureau of Standards
Gaithersburg, MD 20899

Dr. J. M. Peterson
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Dr. M. Piestrup
Adelphi Technology
13800 Skyline Blvd. No. 2
Woodside, CA 94062

Dr. Alan Pike
DARPA
1400 Wilson Boulevard
Arlington, VA 22209

Dr. Hersch Pilloff
Code 421
Office of Naval Research
Arlington, VA 22217

Dr. A. L. Pindroh
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. D. J. Pistoresi
Boeing Aerospace Company
P. O. Box 3999
Seattle, WA 98124-2499

Major E. W. Pogue
SDIO
The Pentagon, T-DE Rm. 1E180
Washington, DC 20301-7100

Dr. Peter Politzer
General Atomic Tech., Rm. 13/260
P. O. Box 85608
San Diego, CA 92138

Major Donald Ponikvar
U. S. Army SDC
P. O. Box 15280
Arlington, VA 22245-0280

Dr. S. E. Poor
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Prof. M. Porkolab
NW 36-213
Mass. Institute of Technology
Cambridge, MA 02139

Dr. R. V. Pound
Physics Department
Harvard University
Cambridge, MA 02138

Mr. J. E. Powell
Sandia National Laboratories
ORG. 1231, P.O. Box 5800
Albuquerque, NM 87185

Dr. Anand Prakash
Ballistic Research Laboratory
Aberdeen Proving Ground, MD 21005

Dr. Mark A. Prelas
Nuclear Engineering
Univ. of Missouri-Columbia
1033 Engineering
Columbia, Missouri 65211

Dr. Donald Prosnitz
Lawrence Livermore National Lab.
Box 5511 L-626
Livermore, CA 94550

Dr. D. C. Quimby
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. Paul Rabinowitz
Xexon Research and Eng. Comp.
P. O. Box 45
Linden, NJ 07036

Dr. G. Ramian
Quantum Institute
University of California
Santa Barbara, CA 93106

Dr. L. L. Reginato
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. M. B. Reid
Dept. of Electrical Engineering
Stanford University
Stanford, CA 94305

Dr. D. A. Reilly
AVCO Everett Research Lab.
Everett, MA 02149

Dr. M. Reiser
University of Maryland
Department of Physics
College Park, MD 20742

Dr. S. Ride
Arms Control
Stanford University
Stanford, CA 94305

Dr. C. W. Roberson
Office of Naval Research
Code 112S
800 N. Quincy Street
Arlington, VA 22217

Dr. B. Robinson
Boeing Aerospace Company
P.O. Box 3999
Seattle, WA 98124

Dr. K. Robinson
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. D. Rogers
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. Jake Romero
Boeing Aerospace Company
P. O. Box 3999
Seattle, WA 98124-2499

Dr. T. Romesser
TRW, Inc.
One Space Park
Redondo Beach, Ca 90278

Dr. Marshall N. Rosenbluth
Dept. of Physics
B-019
Univ. of Calif., San Diego
LaJolla, CA 92093

Dr. J. B. Rosenzweig
The Inst. for Accelerator Physics
Department of Physics
University of Wisconsin-Madison
Madison, WI 53706

Dr. J. Ross
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. N. Rostoker
Department of Physics
University of California at Irvine
Irvine, CA 92717

Dr. Antonio Sanchez
Lincoln Laboratory
Mass. Institute of Tech.
Room B213
P. O. Box 73
Lexington, MA 02173

Dr. Aldric Saucier
BMD-PO
Ballistic Missile Defense
Program Office
P. O. Box 15280
Arlington, VA 22215

Dr. A. Saxman
Los Alamos National Scientific Lab.
P. O. Box 1663, MSE523
Los Alamos, NM 87545

Dr. J. Scharer
ECE Dept.
Univ. of Wisconsin
Madison, WI 53706

Dr. E. T. Scharlemann
L626
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Prof. S. P. Schlesinger
Dept. of Electrical Engineering
Columbia University
New York, NY 10027

Dr. Howard Schlossberg
AFOSR
Bolling AFB
Washington, D.C. 20332

Dr. George Schmidt
Stevens Institute of Technology
Physics Department
Hoboken, NJ 07030

Dr. M. J. Schmitt
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Stanley Schneider
Rotodyne Corporation
26628 Fond Du Lac Road
Palos Verdes Peninsula, CA 90274

Dr. M. L. Scott
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Richard L. Schriever (DP-23)
Director, Office of Inertial Fusion
U. S. Department of Energy
Washington, D.C. 20545

Dr. R. W. Schumacher
Hughes Research Laboratories
3011 Malibu Canyon Road
Malibu, CA 90265

Dr. H. Schwettmann
Phys. Dept. & High Energy
Physics Laboratory
Stanford University
Stanford, CA 94305

Dr. Marlan O. Scully
Dept. of Physics & Astronomy
Univ. of New Mexico
800 Yale Blvd. NE
Albuquerque, NM 87131

Dr. S. B. Segall
KMS Fusion
3941 Research Park Dr.
P.O. Box 1567
Ann Arbor, MI 48106

Dr. Robert Sepucha
DARPA
1400 Wilson Boulevard
Arlington, VA 22209

Prof. P. Serafim
Northeastern University
Boston, MA 02115

Dr. A. M. Sessler
Lawrence Berkeley Laboratory
University of California
1 Cyclotron Road
Berkeley, CA 94720

Dr. W. Sharp
L-626
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. Earl D. Shaw
Bell Laboratories
600 Mountain Avenue
Murray Hill, NJ 07974

Dr. J. P. Sheerim
KMS Fusion
P.O. Box 1567
Ann Arbor, MI 48106

Dr. R. Shefer
Science Research Laboratory
15 Ward Street
Somerville, MA 02143

Dr. R. L. Sheffield
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

Dr. Shemwall
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. Shen Shey
DARPA/DEO
1400 Wilson Boulevard
Arlington, VA 22209

Dr. D. Shoffstall
Boeing Aerospace Company
P.O. Box 3999
Seattle, WA 98124

Dr. I. Shokair
SNLA, Org. 1271
Albuquerque, NM 87185

Dr. J. S. Silverstein
Harry Diamond Laboratories
2800 Powder Mill Road.
Adelphi, MD 20783

Dr. Jack Slater
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. Kenneth Smith
Physical Dynamics, Inc.
P.O. Box 556
La Jolla, CA 92038

Dr. Lloyd Smith
Lawrence Berkeley Laboratory
University of California
1 Cyclotron Road
Berkeley, CA 94720

Dr. Stephen J. Smith
JILA
Boulder, CO 80302

Dr. Todd Smith
Hansen Labs
Stanford University
Stanford, CA 94305

Dr. J. Z. Soln (22300)
Harry Diamond Laboratories
2800 Powder Mill Road
Adelphi, MD 20783

Dr. G. Spalek
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Mrs. Alma Spring
DARPA/Administration
1400 Wilson Boulevard
Arlington, VA 22209

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ATTN: D. Leitner
333 Ravenswood Avenue
Menlo Park, CA 94025

Dr. W. Stein
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. L. Steinhauer
STI
2755 Northup Way
Bellevue, WA 98004

Dr. Efrem J. Sternbach
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Dr. W. C. Stwalley
Iowa Laser Facility
University of Iowa
Iowa City, Iowa 52242

Dr. R. Sudan
Lab. of Plasma Studies
Cornell University
Ithaca, NY 14850

Dr. P. W. Sumner
Hughes Research Laboratory
3011 Malibu Canyon Road
Malibu, CA 90265

Dr. David F. Sutter
ER 224, GTN
Department of Energy
Washington, D.C. 20545

Dr. Abraham Szoke
ML/L-470
Lawrence Livermore Natl. Lab.
P.O. Box 808
Livermore, CA 94550

Dr. T. Tajima
Institute for Fusion Studies
University of Texas at Austin
Austin, TX 78712

Dr. H. Takeda
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. J. J. Tancredi
Hughes Aircraft Co.
Electron Dynamics Division
3100 West Lomita Blvd.
Torrance, CA 90509

Dr. Milan Tekula
AVCO Everett Research Lab.
2385 Revere Beach Parkway
Everett, MA 02149

Dr. R. Temkin (2 copies)
Mass. Institute of Technology
Plasma Fusion Center
Cambridge, MA 02139

Dr. L. Thode
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. Keith Thomassen, L-637
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. Harold Thompson
TRW, Inc.
R1/2120
One Space Park
Redondo Beach, Ca 90278

Dr. Norman H. Tolk
Physics Department
Vanderbilt University
Nashville, TN 37240

Dr. Kang Tsang
Science Applications Intl. Corp.
10260 Campus Point Drive
San Diego, CA 92121

Dr. E. Tyson
Boeing Aerospace Company
P.O. Box 3999
Seattle, WA 98124

Dr. H. S. Uhm
Naval Surface Warfare Center
White Oak Lab.
Silver Spring, MD 20903-5000

Dr. L. Ulstrup
TRW, Inc.
One Space Park
Redondo Beach, Ca 90278

Under Secretary of Defense (R&D)
Office of the Secretary of Defense
Room 3E1006, The Pentagon
Washington, D.C. 20301

Dr. L. Vahala
Physics Dept.
College of William & Mary
Williamsburg, VA 23185

Dr. A. Valla
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. A. Vetter
Boeing Aerospace Company
P.O. Box 3999
Seattle, WA 98124

Dr. A. A. Vetter
Spectra Technology
2755 Northup Way
Bellevue, WA 98004

Dr. G. Vignola
Brookhaven National Laboratories
Associated Universities, Inc.
Upton, L.I., NY 11973

Dr. S. A. Von Laven
KMS Fusion Inc.
Ann Arbor, MI 48106

Dr. John E. Walsh
Wilder Laboratory
Department of Physics (HB 6127)
Dartmouth College
Hanover NH 03755

Dr. Jiunn-Ming Wang
Brookhaven National Laboratories
Associated Universities, Inc.
Upton, L.I., NY 11973

Dr. T-S. Wang
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. J. F. Ward
Physics Department
1049 Randall
University of Michigan
Ann Arbor, MI 48109

Dr. Roger W. Warren
Los Alamos National Scientific Lab.
P.O. Box 1663
Los Alamos, NM 87545

Dr. J. Watson
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

Dr. B. Weber
Harry Diamond Laboratories
2800 Powder Mill Road
Adelphi, MD 20783

Dr. J. T. Weir
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Ms. Bettie Wilcox
Lawrence Livermore National Lab.
ATTN: Tech. Info. Dept. L-3
P.O. Box 808
Livermore, CA 94550

Dr. Mark Wilson
National Bureau of Standards
Bldg. 245, Rm. B-119
Gaithersburg, MD 20899

Dr. H. Winick
Stanford Synch. Rad. Lab.
SLAC Bin 69
P.O. Box 44349
Stanford, CA 94550

Dr. J. Workman
Berkeley Research Associates
P.O. Box 241
Berkeley, CA 94701

Dr. Jack Wong (L-71)
Lawrence Livermore National Lab.
P. O. Box 808
Livermore, CA 94550

Dr. Thomas P. Wright
Sandia National Laboratories
ORG. 1231, P.O. Box 5800
Albuquerque, NM 87185

Dr. J. Wurtele
M.I.T.
NW 16-234
Plasma Fusion Center
Cambridge, MA 02139

Dr. Ming Xie
Dept. of Physics
Stanford University
Stanford, CA 94305

Dr. Edward Yadlowsky
High-Tech Research
P. O. Box 3422
Radford, VA 24143

Dr. Yi-Ton Yan
SSC Central Design Group
c/o LBL 90-4040
University of California
1 Cyclotron Road
Berkeley, CA 94720

Dr. A. Yariv
California Institute of Tech.
Pasadena, CA 91125

Dr. J. Yeh
Allied Corporation
31717 La Tienda Dr.
Westlake Village, CA 91362

Dr. A. Yeremian
Boeing Aerospace Company
P.O. Box 3999
Seattle, WA 98124

Dr. Barbara Yoou
R & D Associates
1401 Wilson Blvd., Suite 500
Arlington, VA 22209

Dr. Li Hua Yu
725B, NSLS
Brookhaven National Laboratory
Upton, NY 11973

Dr. Simon S. Yu
Lawrence Livermore National Laboratory
P. O. Box 808
Livermore, CA 94550

Dr. M. S. Zisman
Lawrence Berkeley Laboratory
University of California, Berkeley
Berkeley, CA 94720

Dr. J. Zumdieck
Spectra Technology
2755 Northup Way
Bellevue, WA 98004